REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE June 28, 1999	3. REPORT TYPE AND DATES COVERED Final Progress 1 Jul 92-30Jun98

4. TITLE AND SUBTITLE
ARO/URI Multidisciplinary Program in Manufacturing Science of Polymeric Composites

5. FUNDING NUMBERS
DAAL03-92-G-0114

6. AUTHOR(S)
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Center for Composite Materials
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Newark, DE 19716-3144

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 30365.1-MS-URI

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

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The University of Delaware conducted a five-year multidisciplinary program in the manufacturing science of polymeric composites. The research effort was coordinated through five major thrust areas. The Advanced Autoclave Molding area addressed issues of batch-wise in-process monitoring and computer-integrated models; emphasis was placed on coupling reaction chemistry and process control to the mechanical performance of thick-section composites. Textile Preforming/Resin Transfer Molding addressed issues of in-process monitoring and computer-integrated models in an approach to developing high-performance, low-cost structures and the basis for studying multi-functional intelligent composites. Sheet and Stretch Forming was

14. SUBJECT TERMS			15. NUMBER OF PAGES
			16. PRICE CODE
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Final Report

ARO/URI Multidisciplinary Program in Manufacturing Science of Polymeric Composites

1992–1998

to
the U.S. Army Research Office

by
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UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

aimed at developing a new manufacturing technology for thermoplastic composites. On-Line Process Control and NDE Inspection served as the focal point for the development of new in-process NDE technology. Intelligent Control of Integrated Manufacturing Processes integrated the process models developed in the other areas into a knowledge-based system (KBS). Overall, the program was aimed at improving the reliability and extending the useful life of structural components through optimization and control of potentially lower-cost manufacturing processes.

Foreword

In 1986, the Army Research Office, through its University Research Initiative Program, established the ARO/URI Center of Excellence for Manufacturing Science, Reliability, and Maintainability Technology at the University of Delaware Center for Composite Materials (CCM). The program strongly emphasized building quality, long life, predictable and reliable performance, durability, and lower life-cycle costs into thick-section composite systems. In 1992, the Center received a renewal grant from ARO to investigate the manufacturing science of polymeric composites. During the past 10 years, the ARO/URI program has become a core initiative for the Center, resulting in the formation of links with other Army organizations and the establishment of additional collaborative programs.

In establishing the URI center at the University of Delaware in 1986, ARO created a national resource that will serve the needs of the "Army After Next" into the twenty-first century. As a result of this multidisciplinary program of basic research and education, the Center for Composite Materials is well-positioned to serve the needs of the Army with an effective and responsive infrastructure, an awareness of Army needs, an established network of Army and industrial collaborators, and the ARL Composite Materials Research (CMR) Collaborative Program to help sustain the momentum developed under the ARO/URI Program.

The following summarizes quantitatively the accomplishments of the ARO/URI Program at the University of Delaware during the past 10 years (i.e., including Phase and Phase II of the ARO/URI):

- 39 ARO Fellows funded
- 22 Ph.D.s & 16 master's degrees awarded
- 360+ related journal & conference papers
- 3 senior design projects completed for Army customers
- 19 faculty/professional staff participants
- 11 articles on CCM published in *Army RD&A Bulletin*
- 131 related CCM technical reports issued
- 2 colleges, 4 departments involved
- 12 Army labs interacting with CCM
- 9 major programs on which ARO/URI at UD has had a significant impact
- 7 Army scientists in residence
- $1.5M for manufacturing and characterization equipment

Less tangible but nevertheless significant are the following elements of the ARO/URI Program legacy at the University of Delaware:

- Development of a new science base for composites manufacturing, including process simulations
- Establishment of a proactive network with Army labs, industry, and ONR for technology transition/implementation
- Creation of an interdisciplinary teaching/learning environment
- Promotion of team building
- Education and training of U.S. students for government, academic, and industrial positions
- Incorporation of composites-related research into the engineering curriculum
- Enhancement of the undergraduate research experience
- Provision of the basis for new educational tools
- Positioning of the Center to attract additional equipment funding through three DURIP grants

Table of Contents

Statement of the problem studied

The multidisciplinary program focused on developing a manufacturing science base for polymeric composites. The research effort was coordinated through five major thrust areas:

1. The **Advanced Autoclave Molding** area addressed issues of batch-wise in-process monitoring and computer-integrated models; emphasis was placed on coupling reaction chemistry and process control to the mechanical performance of thick-section composites.
2. **Textile Preforming/Resin Transfer Molding** addressed issues of in-process monitoring and computer-integrated models in an approach to developing high-performance, low-cost structures and the basis for studying multi-functional intelligent composites.
3. **Sheet and Stretch Forming** was aimed at developing a new manufacturing technology for thermoplastic composites.
4. **On-Line Process Control and NDE Inspection** served as the focal point for the development of new in-process NDE technology.
5. **Intelligent Control of Integrated Manufacturing Processes** integrated the process models developed in the other areas into a knowledge-based system (KBS).

Overall, the program was aimed at improving the reliability and extending the useful life of structural components through optimization and control of potentially lower-cost manufacturing processes.

Summary of the most important results

Development of a new science base

- Integration of chemistry and mechanics—cure, residual stress and warpage
- Reaction kinetics
- Diffusion/healing
- Interphase mechanisms
- Micromechanics—woven structures, interphase
- Heat transfer/fluid flow
- Permeability
- Sensing

Process simulations

- RTM mold filling
- Resin infusion
- Preform permeability/draping
- Manufacture of multi-step braided composites
- Thick-section cure—autoclave, RTM, microwave
- Automated thermoplastic tow placement

Mechanics of thick-section composites

- Developed a methodology to study process-induced stress and deformation accounting for thermomechanical interaction, thermal and chemical shrinkage, spatial solidification, and arbitrary cross-sectional geometry
- Made significant contribution to the fundamental understanding of thick-section processing
- Identified key role of chemical reaction kinetics
- Coupled cure solidification and shrinkage to residual stress and warpage
- Established foundation for cure-cycle optimization

Influence of the interphase on composite properties

- Developed novel techniques for interrogating properties in the vicinity of the fiber surface
- Demonstrated that property gradients of the matrix exist in the vicinity of the fiber:
  - Thermoplastic property gradients result from entropic segregation of molecular weight.
  - Thermoset property gradients result from stoichiometric imbalance due to diffusion of species to fiber surface.
- Developed models to relate property gradients to local states of residual stress

Textile preforming

- Developed a manufacturing science base of textile composites using braiding, weaving, and knitting processes
- Constructed the relationship between manufacturing processes and the resulting microstructures
- Derived analytical models to predict the thermal, mechanical, and physical properties of textile structural composites
- Developed advanced equipment for fabrication and consolidation of textile composites
- Experimentally verified the predictions of the analytical models

Diffusion-enhanced adhesion (DEA)

- Enables bonding of thermoplastics to thermosets
- Grew out of interphase research
- Focused on Composite Armored Vehicle (CAV)
- Achieved superior ballistic and structural performance as demonstrated by UDLP tests

Rapid fiber placement technology (RAPTECH)

- Established fundamentals for thermoplastic processing in first ARO/URI Program (1986–1991)
- Leveraged DARPA funding for continuation
- Developed comprehensive process simulation
- Implemented advanced model-based control
- Transitioned to industry

Sensing and control

- Developed a fundamental understanding of the relevant issues for an on-line quality sensing system for thermoplastic processes
- Developed a fundamental understanding of the relationship between porosity in composite structures and ultrasonic velocities
- Developed a fundamental understanding of the correlations between ultrasonic amplitudes and automated welding of thermoplastics
- Developed a fundamental understanding and explanation of the onset of ablation in laser-based ultrasonics
- Developed a new inspection method (patent pending) for Gas-Coupled Laser Acoustic Detection (GCLAD)

Flow in molding processes

- Demonstrated that permeability and fabric architecture are tied together
- Demonstrated that micro, macro, and transverse flow physics should be included in RTM filling
- Demonstrated the importance of fabric draping/deformation
- Demonstrated that flow simulations do help in-process control and tool design

Liquid Injection Molding Simulation (LIMS) capabilities

- Faster fill algorithm
- Higher precision
- Reasonable void tracking
- Full control over inlets/outlets during simulation
- Full access to simulation data during simulation
- Programming capability—on-line control simulation, simplification of repetitive tasks
- Automatic tracking of gate and node data during filling
- Direct output to PATRAN/TECPLOT
- Expandable
- Targets PCs and low-end workstations

Education

- Created an interdisciplinary environment
- Promoted team building
- Trained U.S. students for Army, academic, and industrial positions
- Moved research into curricula
- Enhanced undergraduate research experience
- Provided basis for new educational tools—NSF manufacturing education program with MSU, Web-based interactive tutorials

Technology transition/implementation

- Established proactive network
  - Army labs (ARL, TARDEC, ARDEC, MICOM, CRREL, CRDEC, BRDEC, etc.)
  - Office of Naval Research (ONR)
  - Industry
- Serves to identify needs of the Army
- Enhances rapid implementation

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Experimental Investigation of Flow Fronts in Resin Transfer Molding
A. R. Spinelli and S. G. Advani

CCM 92-24
Kink-Band Failure Analysis of Thick Composites in Compression
E. T. Camponeschi, Jr., J. W. Gillespie Jr., and D. J. Wilkins

CCM 92-25
Origin and Influence of Interphase Material Property Gradients in Thermosetting Composites (Ph.D. dissertation)
G. R. Palmese(advisor: R. L. McCullough)

CCM 92-31
Intelligent Manufacturing of Filament-Wound Structures
C. B. Ebersold and S. G. Advani

CCM 92-35
Effective In-Plane Permeability of Multi-Layered RTM Preforms
M. V. Bruschke, T. L. Luce, and S. G. Advani

CCM 92-40
Local Methods for Optimization of Batch Processes
V. Pillai, A. N. Beris, and P. S. Dhurjati

CCM 92-42
Resistance Welding of Dual-Polymer Composites Using a Statistically Designed Experimental Approach
I. Howie, J. W. Gillespie Jr., and A. J. Smiley

CCM 92-43
Resistance Heated Dual Resin Bonding
S. H. McKnight, S. T. Holmes, I. Howie, K. D. Tackitt, J. W. Gillespie Jr., and A. J. Smiley

CCM 92-48
Resin Transfer Molding in Flow Phenomena in Polymeric Composites
S. G. Advani and M. V. Bruschke

CCM 92-50
FEA Techniques for Analyzing Residual Stresses During In-Situ Filament Winding of Complex Geometries Using ABAQUS®
D. D. Coppens, B. Powers, J. W. Gillespie Jr., and R. F. Eduljee

CCM 92-53
A Review of Consolidation Mechanics in Composites Processing
H. H. Lin and S. G. Advani

CCM 92-55
Resistance-Heated Fusion Bonding of Carbon Fiber/PEEK Composites and 7075-T6 Aluminum
S. H. McKnight, S. T. Holmes, J. W. Gillespie Jr., C. L. T. Lambing, and J. M. Marinelli

CCM 92-56
A Predictive Model for Permeability and Non-Isothermal Flow of Viscous and Shear-Thinning Fluids in Anisotropic Fibrous Media (Ph.D. dissertation)
M. V. Bruschke (advisor: S. G. Advani)

List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project

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Roy L. McCullough, Chemical Engineering; Materials Science & Engineering

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Richard W. Rydin
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Ph.D. degrees awarded

James N. Caron (Ph.D. Physics '97): *Application of Laser Ultrasonics to Graphite/Polymer Composite Materials*

Jeffrey A. Hrivnak (Ph.D. ChE '97): *Interphase Formation in Reacting Systems*

Eric J. Lang (Ph.D. ME '97): *Intelligent Textile Composite Materials Containing Lineal Strain Sensors*

David L. Fecko (Ph.D. MSE '96): *In-Situ Ultrasonic Porosity Monitoring for the Thermoplastic Matrix Pultrusion Process*

Richard W. Rydin (Ph.D. MSE '96): *Using the Drop Weight Impact Tower to Evaluate the Impact Resistance of FRP Composite Plates*

Stephen F. Shuler (Ph.D. ME '96): *Rheology and Forming of Long-Fiber- Reinforced Thermoplastic Composite Materials*

Vikram K. Pillai (Ph.D. ChE '94): *Use of Simulations in Optimization of, and Development of a Knowledge-Based System for, a Composites Manufacturing Process*

David A. Steenkamer (Ph.D. ME '93): *The Influence of Preform Design and Manufacturing Issues on the Processing and Performance of Resin Transfer Molded Parts*

Master's degrees awarded

Kenric M. England (M. MSE '97): *Direct Current Sensing of Viscosity and Degree of Cure of Vinyl-Ester Resins*

Jeffrey Mogavero (M. ME '97): *Compression Characterization and Resin Infiltration of Multi-Layered Preforms in Resin Transfer Molding*

Thomas L. Luce (M. ME '96): *An Experimental Investigation of the In-Situ In-Plane and Transverse Permeabilities of Fiber Preforms*

Dennis J. Michaud (M. ChE '96): *Investigation of Curing Behavior in Thick Thermoset Composites Manufactured by Resin Transfer Molding*

Scott T. Holmes (M. ME '95): *Influence of Surface Modification on the Processing and Performance of Aluminum Adhesive Joints Bonded with Thermoplastic Polymers*

James N. Caron (M.S. Physics '95): *Methods for Studying Ablation Phenomena Using Laser Ultrasonics*

Stephanie L. Nesbitt (M. ChE '95): *Cure Chracterization of Bismaleimides*

Jeffrey A. Hrivnak (M. ChE '94): *Optimization of the Surface Free Energy on Carbon Fibers and its Effect on Interphase Formation*

Michael T. Qaissaunee (M. ME '93): *Interaction Between and Edge Dislocation and a Single-Phase and Two-Phase Elliptical Inclusion*

Report of inventions

Gas-Coupled Laser Acoustic Detection, J. N. Caron, J. B. Mehl, and K. V. Steiner, U.S. Patent Application Serial No. 08/840,968, 1998.